

# Linear non-hysteretic gating of a very high density 2DEG in an undoped metal-semiconductor-metal sandwich structure

K. Das Gupta,<sup>1,2,\*</sup> A. F. Croxall,<sup>1</sup> W.Y. Mak,<sup>1</sup> H. E. Beere,<sup>1</sup> C. A. Nicoll,<sup>1</sup> I. Farrer,<sup>1</sup> F. Sfigakis,<sup>1</sup> and D. A. Ritchie<sup>1</sup>

<sup>1</sup>*Cavendish Laboratory, J.J. Thomson Avenue, Cambridge CB3 0HE, UK.*

<sup>2</sup>*Indian Institute of Technology Bombay, Mumbai 400 076, India*

Modulation doped GaAs-AlGaAs quantum well based structures are usually used to achieve very high mobility 2-dimensional electron (or hole) gases. Usually high mobilities ( $> 10^7 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ ) are achieved at high densities. A loss of linear gateability is often associated with the highest mobilities, on account of some residual hopping or parallel conduction in the doped regions. We have developed a method of using fully undoped GaAs-AlGaAs quantum wells, where densities  $\approx 6 \times 10^{11} \text{cm}^{-2}$  can be achieved while maintaining fully linear and non-hysteretic gateability. We use these devices to understand the possible mobility limiting mechanisms at very high densities.

Keywords: undoped quantum well, double-side processing, etch-stop layer, backgate

The ability to tune the carrier density of a 2-dimensional electronic system (2DES) over large ranges with a linear and non-hysteretic gate is one of the most desirable and generic aspects in experiments that involve a 2DES. Fundamental aspects of a 2DES, like the ratio of Coulomb and kinetic energy, screening, relative importance of various scattering mechanisms are all functions of the carrier density. The low density end ( $\sim 10^9 \text{cm}^{-2}$  and lower) is of great interest because the very dilute 2DES is a strongly interacting system[1], where the Coulomb interaction energy outweighs the kinetic energy. On the other hand the very high density end ( $10^{11} - 10^{12} \text{cm}^{-2}$ ) is of interest because the highest electron mobilities [2] can be achieved at these densities. Qualitatively, this happens because the effect of ionized impurity scattering diminishes as  $k_F$  (the Fermi wavevector) becomes larger compared to the Fourier components of the impurity potential ( $\sim e^{-qd}/q$ , where  $q$  is the scattering wavevector and  $d$  is the distance of the ionized impurity from the plane of the 2DES). Study of several other phenomena like non-parabolic effects and anti-crossing of hole bands[3], mobility limiting effect of interface roughness [4], study of novel Fractional Quantum Hall (FQHE) states [5, 6] also require single-subband, parallel-conduction free, linearly gateable, non-hysteretic 2DES in the density range ( $10^{11} - 10^{12} \text{cm}^{-2}$ ).

The advent of the quantum well structure with modulation doping [7] and an undoped spacer allowed higher densities and mobilities to be reached compared to what was possible with a heterostructure. Such structures have been the workhorse for 2DES based devices for last 30 years. But a limitation of this scheme becomes apparent at high densities (Fig. 1 (a)&(b)). As the (as grown) carrier density is increased by increasing the doping concentration the slope of the conduction band (CB) just outside the well must also increase. This is necessary to satisfy electrostatics, because the flux of the electric field

(slope of the conduction band) over a box that encloses the quantum well must equal the charge contained within. But the sharper slope of the conduction band forces the impurity band ( $\sim 30 \text{meV}$  below CB in  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ ) to come closer to the electrochemical potential. Thus high doping also makes devices more prone to unwanted hopping/parallel conduction. Variants of the modulation doping scheme like short-period-superlattice (SPSL) [2] doping cannot circumvent this basic problem. In fact it has been acknowledged in recent literature that the highest mobility 2DES also suffers from some amount of hysteresis and is often not linearly gateable owing to slow charge transfer/relaxation in the dopant layers[8]. The significance of linear gateability at high densities for understanding the ( $\nu = 5/2$ ) FQHE state have also been highlighted recently[5, 6]. Indeed the presence of small amounts of parallel conducting channels would cause the Hall plateaus to lose exact quantization and the zeros of the Shubnikov de-Haas oscillations to lose their sharp definition. We shall show in this paper that gateability of the 2DES is also crucial for positioning the envelope of the carrier wavefunction in the quantum well for obtaining the maximum mobility.

We describe the growth, fabrication and initial measurements on devices where linear gating is demonstrated from  $< 4 \times 10^{10} \text{cm}^{-2}$  to  $\sim 6 \times 10^{11} \text{cm}^{-2}$  in a 20nm wide (GaAs-AlGaAs) quantum well. The highest electron mobility we achieve is  $\mu_e \approx 9 \times 10^6 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$  at  $T=1.5\text{K}$ . We present some data indicative of the mobility limiting scattering mechanism at the highest density. Finally we discuss, how the range of the densities can be increased further and the possible iterative improvement of growth conditions to improve the mobilities.

Fig. 1(c) & (d) shows the basic idea behind our method. If a very thin (1-2 $\mu\text{m}$ ), completely undoped AlGaAs-GaAs-AlGaAs can be sandwiched between two layers of metals, then the backgate and topgate bias on these plates ( $V_{BG}$  and  $V_{TG}$  w.r.t. the ohmics which connect to the quantum well) can be used to attract carriers into the well. There is no intentional dopant

\*Electronic address: kd241@cam.ac.uk, kdasgupta@phy.iitb.ac.in

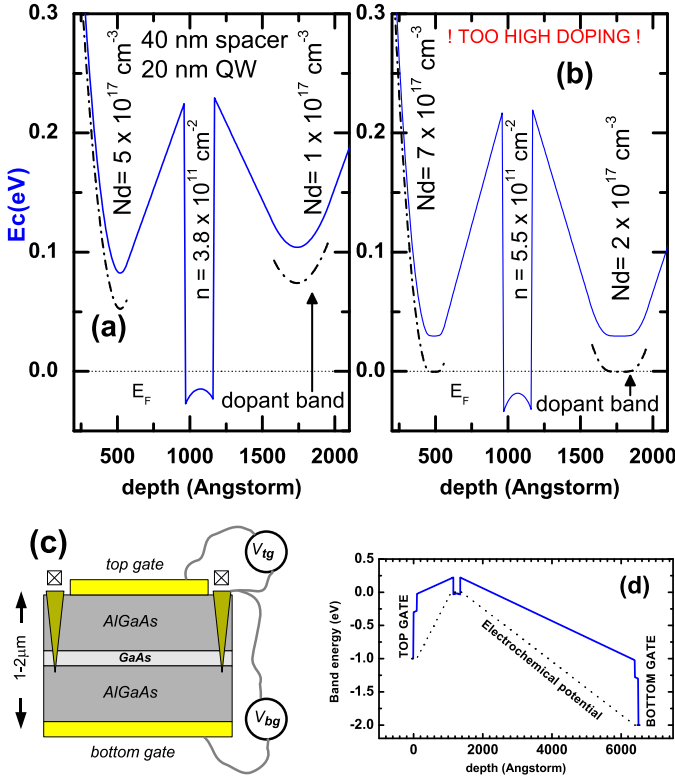


FIG. 1: (Colour online)(a) & (b) Example of a self consistent band structure around a typical GaAs-AlGaAs quantum well. Notice how the dopant band drops and touches the electrochemical potential at high doping levels.(c) The basic idea behind the fully undoped metal-semiconductor-metal sandwich structure, that can be kept free of parallel conduction at high densities (d) The expected variation of the electrochemical potential across the sample. The numbers are approximate.

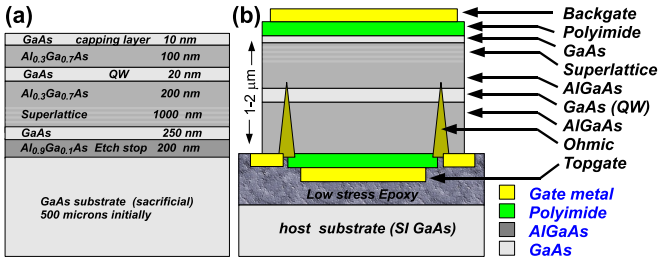


FIG. 2: (a) Layering of the wafer used to make the devices. (b) Schematic of the device. Note that the device is turned upside down after finishing the topside processing.

layer anywhere. The electrochemical potential itself goes down as one moves out from the quantum well, because the positive voltage bias on the gates are set to attract electrons (positive bias lowers the electrochemical potential). The combination of these two ensure that there is no place for parallel conduction to develop. Also the relative bias on the two gates can be adjusted to tune the shape and tilt of the wavefunction in the quantum well. Two practical considerations are however needed at this point. First there must be ohmic contacts

going into the quantum well. Second, the 1-2  $\mu\text{m}$  thick sandwiched structure cannot be self-supporting. Thus the fabrication method has to ensure alignment of the topside and bottom side features, as well as stress-free embedding of this structure in a suitably rigid base. Our fabrication method achieves these. The packaged devices showed no cracking after several thermal cycles from room temperature to 1.5K. The densities and mobilities obtained from measurements in two different cryostats agreed within  $\sim 10\%$

The wafer used in this study was grown on a 500  $\mu\text{m}$  [100] GaAs substrate as shown in Fig. 2a. The quantum well was located approximately 100nm below the surface and the etch stop ( $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ ) was approximately 1500nm below the surface. The topside processing consisted of four main steps. A Hall bar shaped mesa was etched (150-200nm) and ohmics were lithographically defined. AuGeNi contacts were annealed at 450°C for 180sec in a reducing atmosphere ( $\text{N}_2/\text{H}_2$ ) after liftoff. A layer of polyimide (HD 4104, HD microsystems) was then spin coated on the sample. The polyimide layer was 400-500nm thick after curing at 250°C. A metal topgate (Ti/Au) was patterned and deposited on top of the polyimide layer. After this the sample was embedded topside down on a host (GaAs wafer) with a thin layer of epoxy. The GaAs substrate was then removed from the back using a combination of abrasive mechanical polishing and selective etching (in Citric-acid+ $\text{H}_2\text{O}_2$ ) etch to expose the  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  etch stop. The etch stop was then removed using Hydrofluoric acid (HF). The HF removes the etch stop due to its high Al concentration but does not attack the GaAs layer below. At this stage a smooth mirror finish is obtained. A careful inspection is done for any cracks and deformations. The sample is then coated with another layer of polyimide and the backgate is deposited on top of the cured polyimide. During this last stage the bond pads to the sample are also defined, which are then used to connect the ohmics and the gates to a leadless chip carrier using an ultrasonic wire bonder. A similar use (with some differences) of epoxy embedding and etch-stop layer was introduced by Weckworth *et al*[13] for fabricating backgates on a bilayer 2DES.

Fig 3a shows that combination of the topgate voltage ( $V_{TG}$ ) and bottom gate voltage ( $V_{BG}$ ) induces a 2-dimensional electron gas (2DEG) in the quantum well. The proof that the channel indeed forms in the quantum well and not somewhere else is provided by the clean Quantum Hall traces. It is impossible to have a high mobility (close to  $10^7 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ) single subband 2DEG anywhere else (*e.g.* the superlattice). The single subband nature of the 2DEG is established by the complete agreement (better than 1 part in 100) of the densities calculated from the slope of the Hall voltage and the period of the oscillations. From the slope of the density of the 2DEG ( $n$ ) vs  $V_{TG}$  and  $V_{BG}$  we can calculate the capacitance of the gates to the 2DEG. This agrees well with the calculated values obtained using the known thickness of the

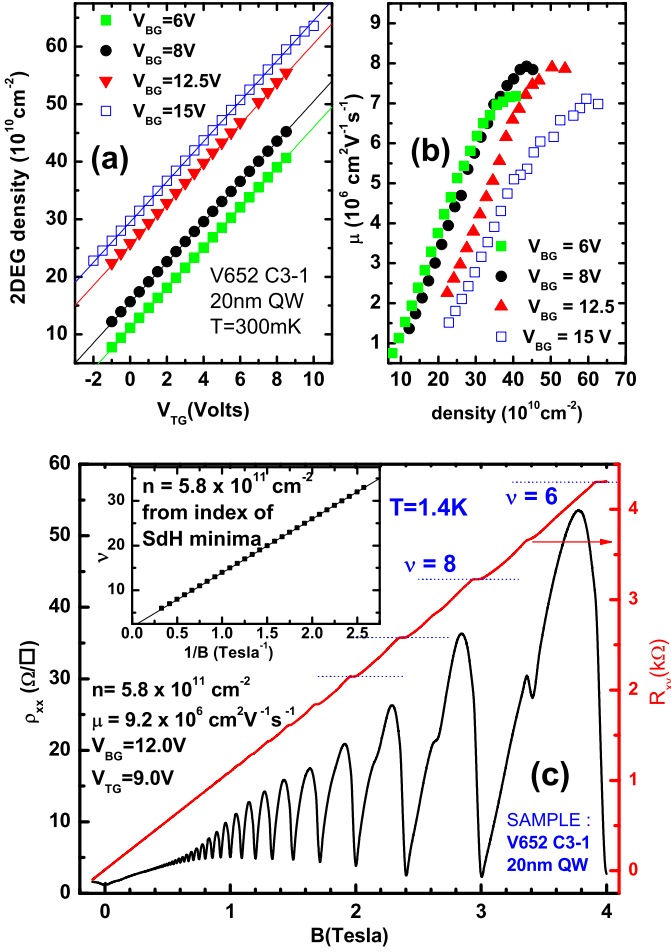


FIG. 3: (Colour online)(a) Linear gateability of the 2-dimensional electron gas (2DEG) till  $6 \times 10^{11} \text{ cm}^{-2}$  (b) the mobility of the 2DEG as a function of density for different backgate voltages. (c) Agreement of the slope of the Hall resistance and the period of oscillation of the Shubnikov de-Haas minima, shows that the 2DEG is indeed in a single subband regime.

semiconductor and polyimide layers.

$$n = \frac{C_{TG}}{e} V_{TG} + \frac{C_{BG}}{e} (V_{BG} - V_0) \quad (1)$$

where  $C_{TG}$  and  $C_{BG}$  denote the topgate and backgate capacitances. We associate a threshold voltage ( $V_0$ ) with the backgate because the specific design of our device uses the backgate to activate the ohmics.  $V_0 \sim 4 \text{ V}$  in our devices.

Since both  $V_{TG}$  and  $V_{BG}$  may be used to tune the carrier density, it is possible to obtain the same density for a number of combinations of the two voltages. In these different combinations  $n$  is same but the shape of the wavefunction is different. Fig 3b shows that the

mobility of the electron gas can vary by nearly 50% depending on the choice of the two gate voltages for the same  $n$ . For example if we examine the four traces in Fig 3a, we find that the density of  $n = 4 \times 10^{11} \text{ cm}^{-2}$  may be obtained by setting  $V_{BG} = 6 \text{ V}$  and  $V_{TG} = 8.25 \text{ V}$ , (green filled square) or  $V_{BG} = 15 \text{ V}$  and  $V_{TG} = 3.0 \text{ V}$  (blue empty square). Fig 3b shows that the mobility in the first case  $7.2 \times 10^6 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  but in the second case it is only  $5.0 \times 10^6 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ . Indeed the large difference in the four traces in Fig. 3b indicates that in the highest mobility regime the ionized background is not necessarily the dominant factor determining the mobility. In a quantum well, we necessarily have two GaAs-AlGaAs interfaces. Inevitably the first of the interfaces (in order of growth) is "inverted" (GaAs is grown on top of AlGaAs) and is thought to have more interface roughness than the other interface in which AlGaAs is grown on GaAs. The relative proximity of the wavefunction to these interfaces will determine the amount of interface roughness scattering experienced by the electrons. In our devices a larger  $V_{BG}$  leads to lower mobilities because the wavefunction is then tilted more towards the inverted interface. In both cases the electrons see a similar ionized background resulting from the unintentional impurities incorporated during MBE growth remains the same[9]. The small change in the form factor of the wavefunction resulting from the change in tilt, cannot account for the large change in screening (or the dielectric function) that would be required to account for a large change in mobility. Coulomb scattering arising from ionized impurities cannot account for this change, leaving the roughness of the interface as the only possible source of the observed change in mobility.

Undoped heterostructures have been known to be particularly useful for maintaining high mobility at low densities [1, 10–12], making very shallow gateable 2DEGs [4]. In this paper we have shown that the field-effect mechanism of pulling carriers from the ohmics into the conducting channel, can be useful in reaching very high densities as well. Our method applies equally well for creating an electron or a hole type channel. Our method requires the MBE chamber used for growth to be optimized for the lowest possible unintentional background and interface roughness once - and not separately for n-type/p-type dopants (which is essential if modulation doping, or any of its variants, is used). The experimenter can decide whether to fabricate n-type or p-type ohmic contacts. It is clearly possible to make these devices fully ambipolar by fabricating both n-type and p-type ohmics on the same Hall-bar. We anticipate that gateable higher densities could also possibly be used to increase the energy gaps of fragile FQHE states by forcing the same filling factor to occur at higher magnetic fields.

- (2009)
- [3] R. Winkler, *Spin orbit coupling effects in two dimensional electron and hole systems*, Springer Publishers (2003)
  - [4] W.Y. Mak K. Das Gupta, H.E. Beere, I. Farrer, F. Sfigakis and D.A. Ritchie . *Applied Physics Letters*, **97**, 242107 (2010)
  - [5] J. Nübler, V. Umansky, R. Morf, M. Heiblum, K. von Klitzing, and J. Smet, *Physical Review B* **81**, 035316 (2010)
  - [6] S. Das Sarma, G. Gervais, and Xiaoqing Zhou, *Physical Review B* **82**, 115330 (2010).
  - [7] R. Dingle, H. L. Störmer, A. C. Gossard, and W. Wiegmann *Applied Physics Letters***33**, 665 (1978)
  - [8] C. Rössler, T. Feil, P. Mensch, T. Ihn, K. Ensslin, D. Schuh and W Wegscheider *New Journal of Physics*, **12**, 043007 (2010)
  - [9] Using methods developed by us earlier[4], we estimated the background in the growth chamber to be approximately  $7 \times 10^{13} \text{cm}^{-3}$  in GaAs and  $1.4 \times 10^{14} \text{cm}^{-3}$  in  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ .
  - [10] B. E. Kane, L. N. Pfeiffer, K. W. West, and C. K. Harnett, *Applied Physics Letters*, **63**, 2132 (1993)
  - [11] R.H. Harrell, K.S. Pyshkin, M.Y. Simmons, D.A. Ritchie, C.J.B. Ford, G.A.C. Jones, and M. Pepper, *Applied Physics Letters* **74**, 2328 (1999)
  - [12] S. Sarkozy, K. Das Gupta, C. Siegert, A. Ghosh, M. Pepper, I. Farrer, H. E. Beere, D. A. Ritchie and G. A. C. Jones, 2009, *Applied Physics Letters*, **94**, 172105 (2009)
  - [13] M.V. Weckwerth, J.A. Simmons, N.E. Harff, M.E. Sherwin, M.A. Blount, W.E. Baca, H.C. Chui, *Superlattices and Microstructures* **20**, 561 (1996)